# Challenges for an Detector for Higgs Physics at the ILC

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DESY

5.10.2015

**CPAD Instrumentation Frontier Meeting**
October 5-7, 2015, Arlington / TX

# Challenges for an Detector for Higgs Physics at the ILC - and other $e^+e^-$ projects


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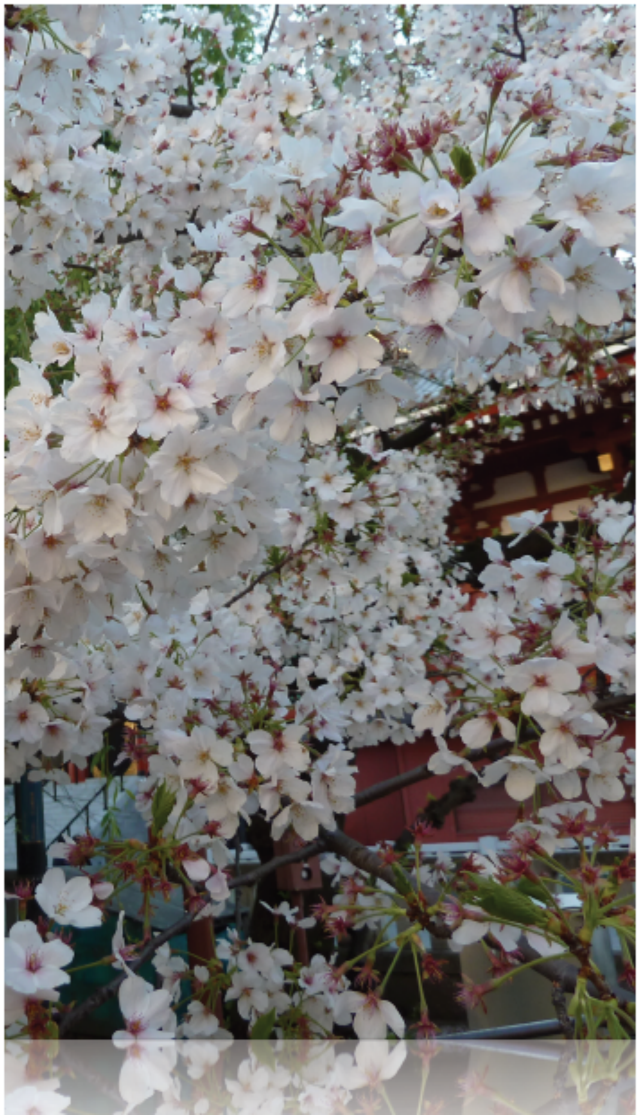
# Outline



- Introduction:
  - What we need to learn about the Higgs in $e^+e^-$ collisions
- The International Linear Collider and other $e^+e^-$ projects
  - Accelerator properties
  - Key detector requirements
- Detector Challenges – taking a closer look at four examples
- Conclusions

# Introduction: What we need to learn about the Higgs in $e^+e^-$ collisions

# After the Discovery...

With the discovery of a Higgs boson, we are just at the beginning:

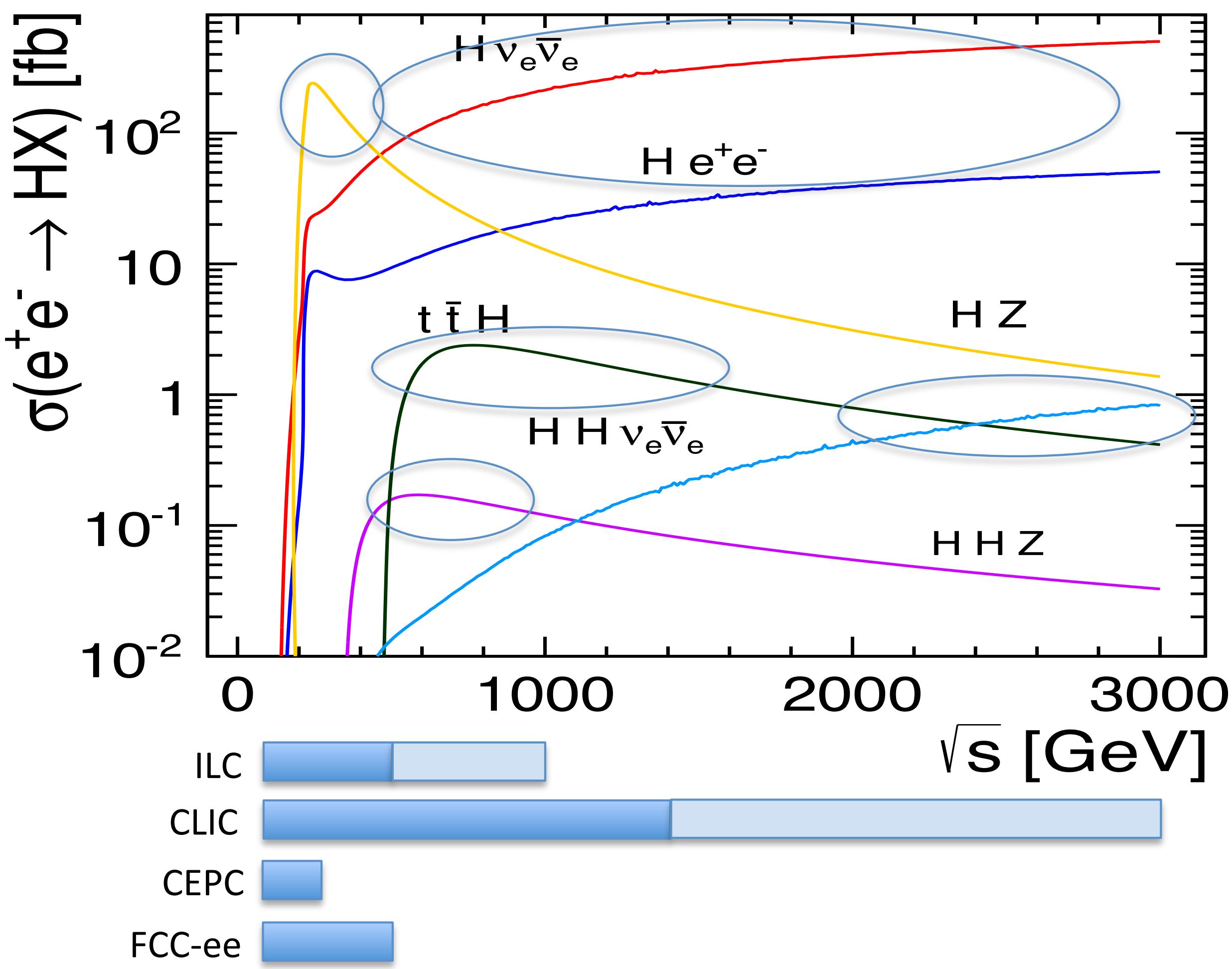
- **What is the physics behind EW symmetry breaking (EWSB)?**
- **What stabilizes the Higgs mass at the EW scale?**
- **Is the Higgs boson related to Dark Matter? Inflation? Baryogenesis? Or even Dark Energy?**

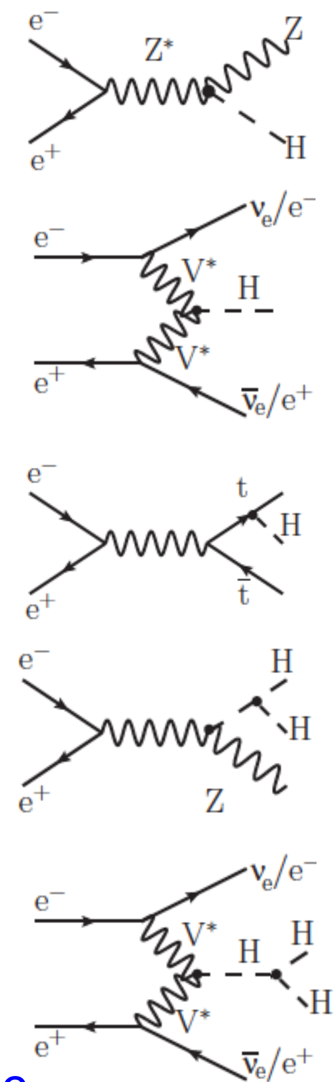
Our gateway to answer these and many other questions:

The **Higgs boson** and the top quark are crucial probes for the mechanism of EWSB

- **A full, model-independent, high-precision profile of the 125 GeV Higgs boson and the top quark**
- **Searches for additional Higgs bosons**
- **Searches for partners of the Higgs: eg Higgsinos**

# The $e^+e^-$ Higgs Precision Program




Mass
$g_Z$ (m.i.)
BR´s
(LHC)-invisible

$\Gamma_{tot}$

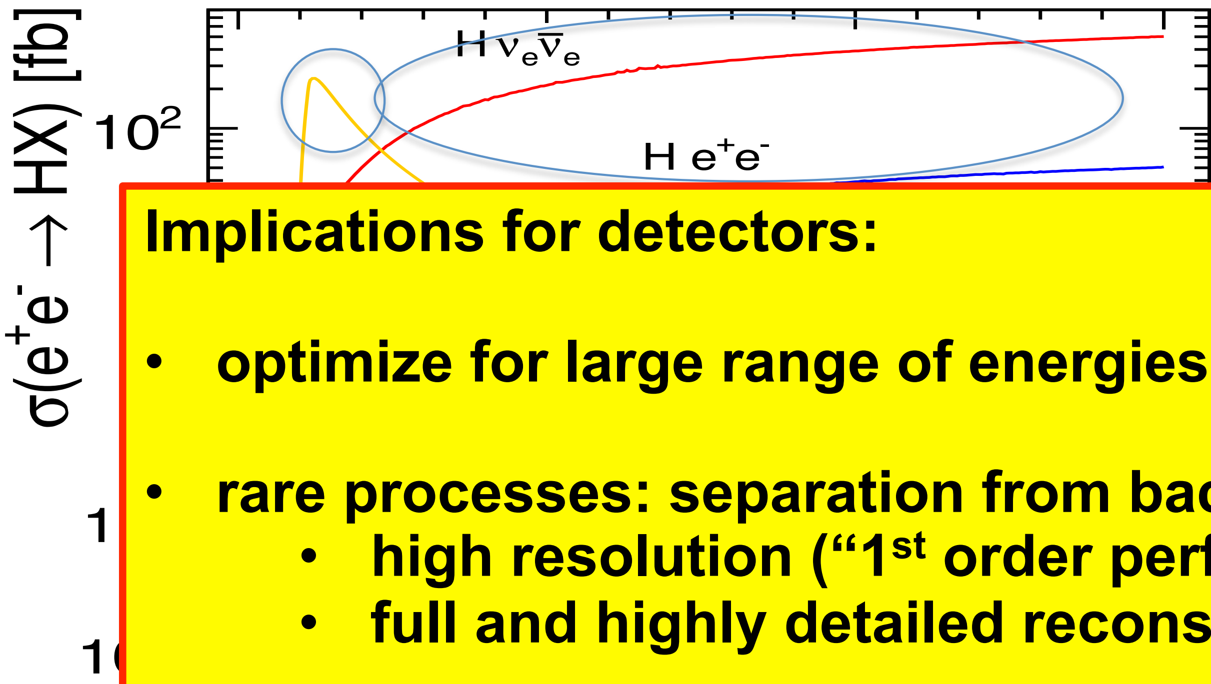
$g_t$

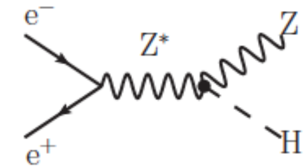
$g_{HHH}$

$g_{HHH}$

- Many processes at different √s needed & accessible

# The $e^+e^-$ Higgs Precision Program




Mass
$g_Z$ (m.i.)
BR´s
(LHC)-invisible

**Implications for detectors:**

- **optimize for large range of energies**
- **rare processes: separation from backgrounds**
  - **high resolution ("1st order performance")**
  - **full and highly detailed reconstruction of each event**
- **high-statistics processes: systematics decisive**
  - **not only resolution**
  - **but also stability, calibration, alignment... ("2nd order performance")**


- Many processes at different √s needed & accessible

# The $e^+e^-$ Higgs Precision Program

**Unique in $e^+e^-$:**
**measurement of the total ZH cross-section => the key to**

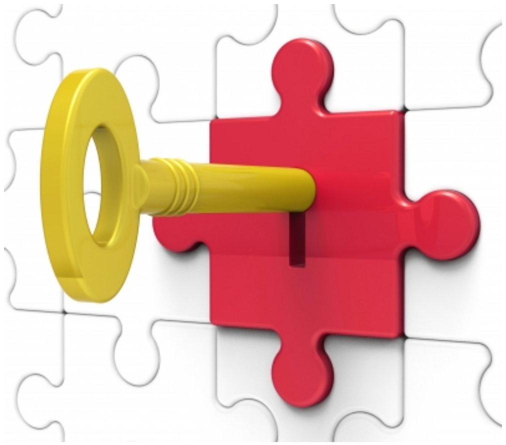


Image courtesy of Stuart Miles at FreeDigitalPhotos.net

- absolute normalization of all couplings
- access to total width
- invisible decays

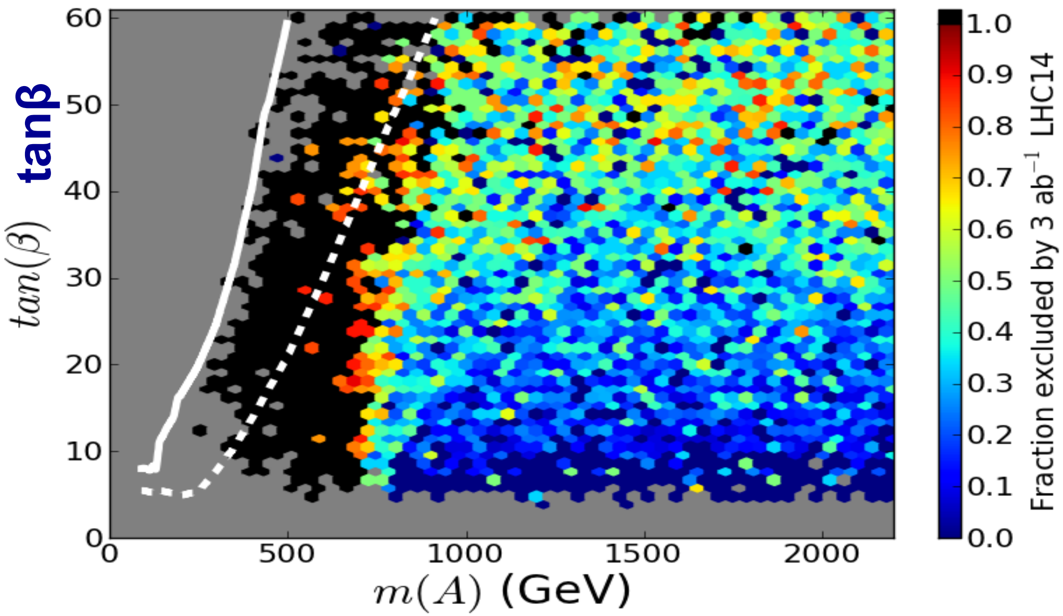
enables a model-independent interpretation of all other measurements – from hadron colliders & $e^+e^-$

- $\sigma$ x BR,
  incl. bottom, charm, gluon, $\tau$...
- direct measurement of $y_t$
- CP admixtures
- ultimate challenge: self-coupling $\lambda_{HHH}$

**Requirement: do this with sufficient precision to be sensitive to new physics effects!**

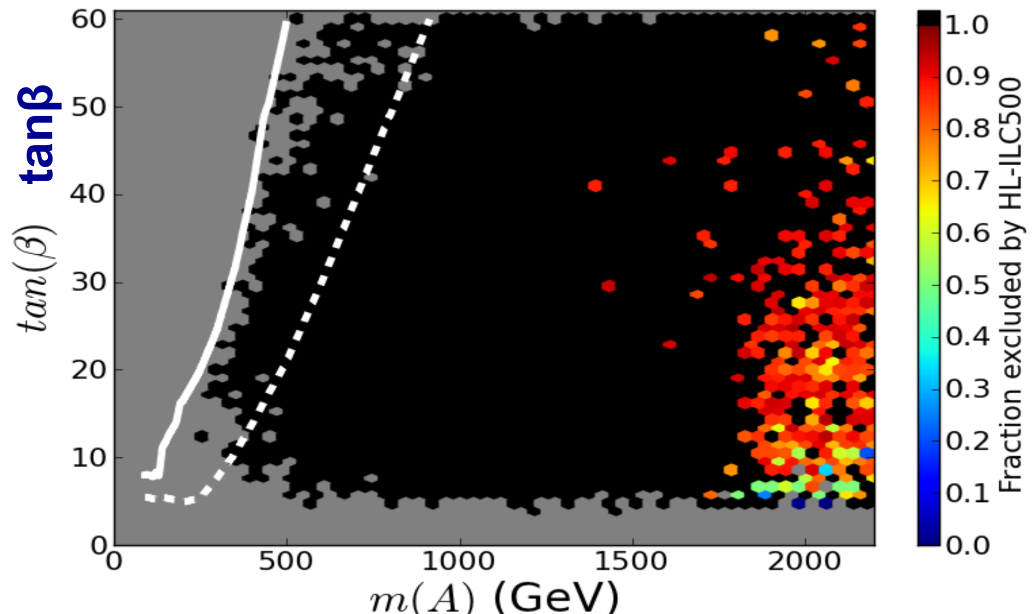
# Example: constraints on pMSSM from hγγ, hττ, hbb

**HL-LHC 3000 fb-1**




**Heavy Higgs mass**

**ILC (1150 fb$^{-1}$@250 GeV & 1600 fb$^{-1}$@500 GeV**




**Heavy Higgs mass**

[Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]]

**Precision Higgs coupling measurements**
**sensitive probe for heavy Higgs bosons**
**$m_A$ ~ 2 TeV reach for <u>any</u> tanβ at the ILC**

# Searches for additional Higgs bosons

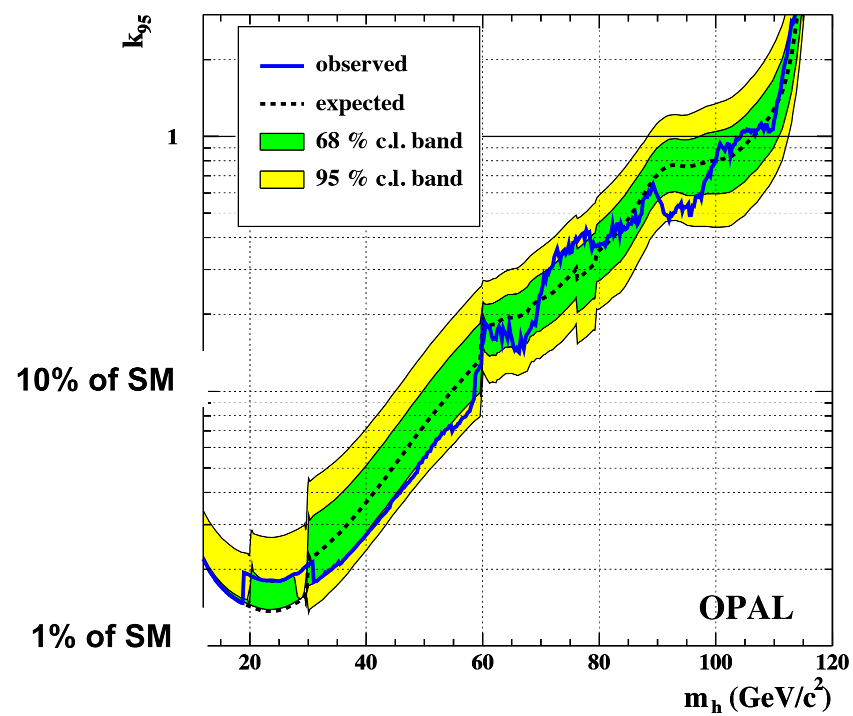
Since H125 looks roughly SM-like, additional Higgs bosons must have suppressed couplings to the Z boson

- "heavy": H, A, $H^{\pm}$, $H^{\pm\pm}$, ...
- **"light", with suppressed couplings to Z**: e.g. **h, a** in NMSSM

low mass region difficult for LHC

LEP limits still the best we have
[here e.g. h->hadrons, flavor independent]

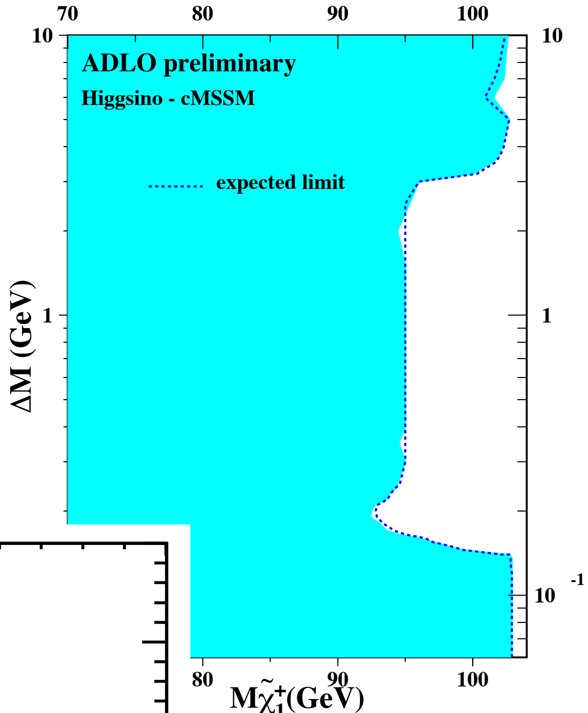
**leaves lot of opportunities for discoveries with the luminosity and beam polarization of future $e^+e^-$ colliders!**



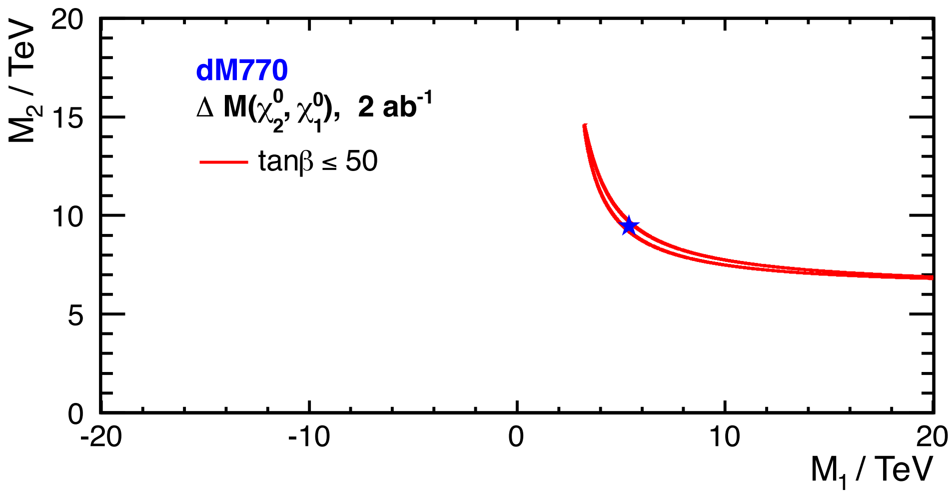
# Higgs Partners: Higgsinos

partners of the Higgs(es) naturally expected near EW scale
[c.f. e.g. H. Baer et al Phys.Rev.Lett. 109 (2012) 161802]

- if other new particles heavy => near-degenerate
- mass splittings ≈< 10 GeV, even sub-GeV
- very few and soft visible decay products
  => extremely challenging for LHC
  => also challenge for ILC detectors!
- but: offers sensitivity to multi-TeV physics!



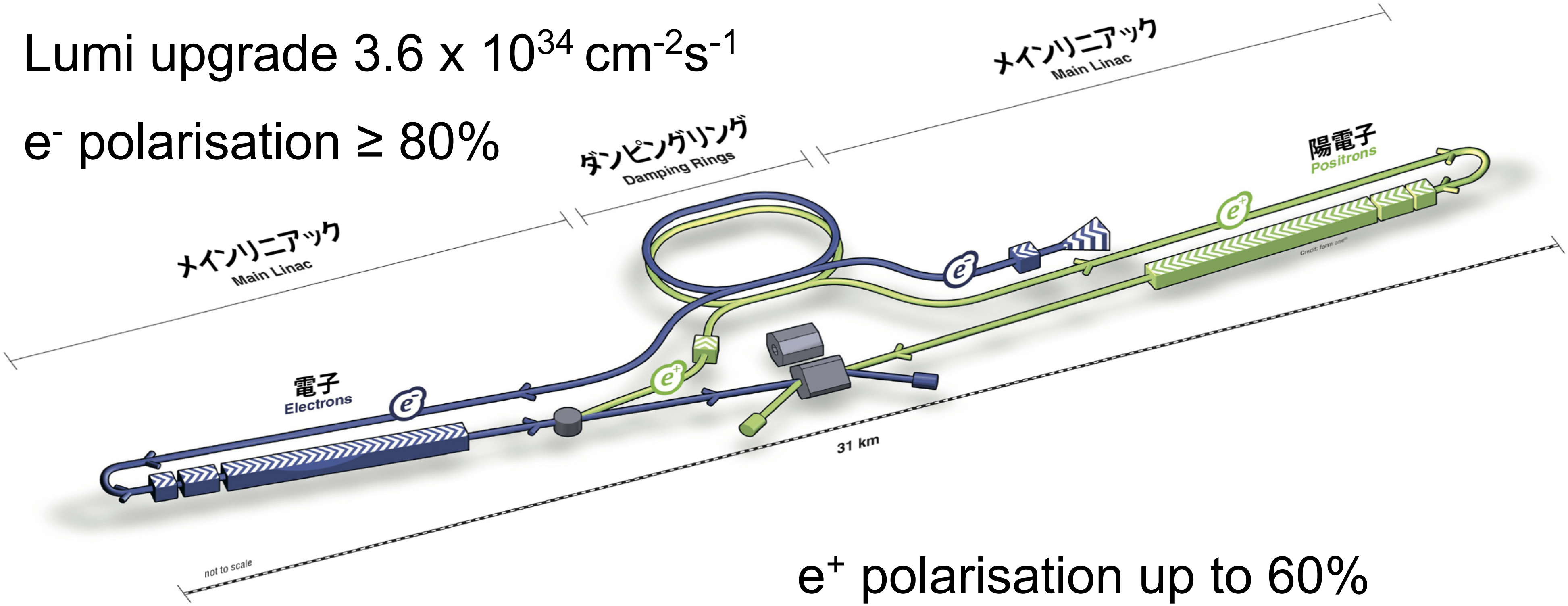

**Higgsino parameter determination at ILC when detector challenges solved**



# The International Linear Collider and other $e^+e^-$ Projects

# The International Linear Collider

- $e^+e^-$ collisions with $\sqrt{s}$ = 200...500 GeV, upgradable to 1 TeV
- Baseline luminosity at 500 GeV:
  $1.8 \times 10^{34}\ cm^{-2}s^{-1}$
- Lumi upgrade $3.6 \times 10^{34}\ cm^{-2}s^{-1}$
- $e^-$ polarisation ≥ 80%

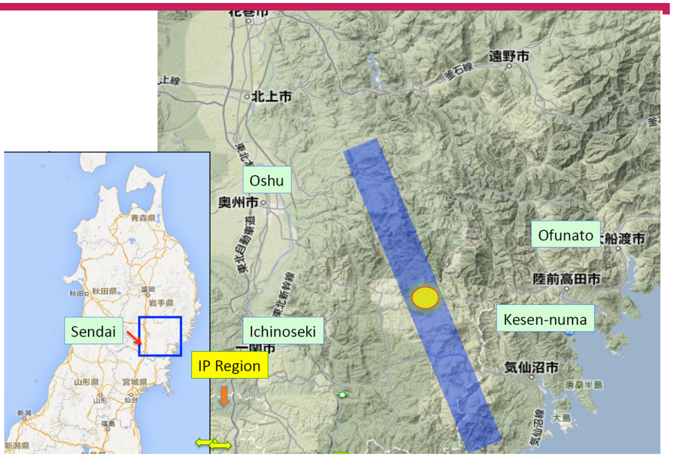



ILC Scheme | ©www.form-one.de

$e^+$ polarisation up to 60%

… and it is a global project!

# ILC Status [K.Desch, DESY Theory WS 2015]




- technically ready to be built
- site chosen (Kitakami, northern Japan)
- interest from Japanese government to host ILC as international project
- internal expert review at MEXT (Japanese science ministry)
  Physics – Cost – International Sharing
  Final report: spring 2016
  Behind the scenes: a lot...

Any reason to be optimistic:
- Japan very interested in large international lab (political top theme – far beyond physics)
- Strong statements in regional strategies (EU, US, Asia, ICFA)
- Strong physics case – even if no additional LHC discovery in near future

# And its detector concepts

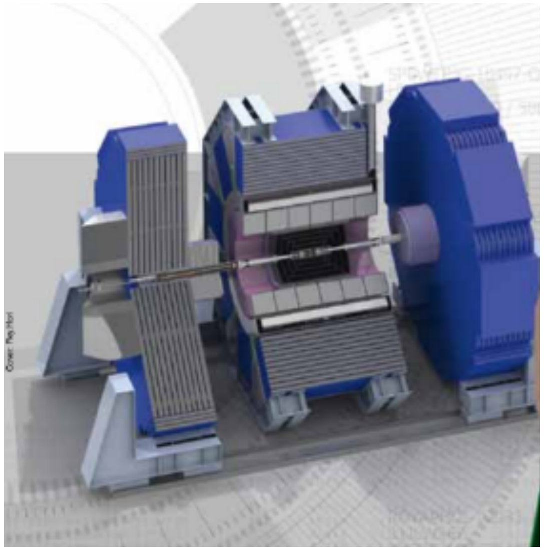
SiD

Tracker

- all Si
- R = 1.2m

B-field

- 5 T



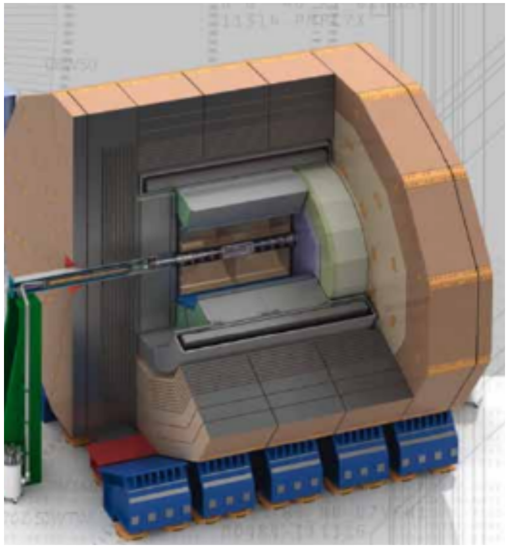
ILD

Tracker

- TPC + Si
- R = 1.8m

B-field

- 3.5 T



Common key design criteria:

- momentum resolution (=> total ZH x-section)
- vertexing (=> flavor tag, H-> bb/cc/ττ)
- jet energy resolution (=> total ZH x-section, H-> invis, ...)
- hermeticity (=> H-> invis, Higgsinos, ...)

⇒ low mass tracker (eg VTX: 0.15% rad. length / layer)

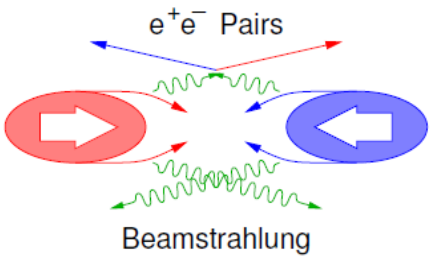
⇒ high granularity calorimeters optimised for particle flow

# Operating the ILC

- pulsed operation:
  - trains of $N_{bunch}$ = 1315 / 2625 bunches, **530 / 270 ns bunch spacing**
  - train repetition rate: 5 – 10 Hz => 199 – 99 ms break

**enables**
- **triggerless readout of detectors => sensitivity to “subtle” signatures**
- **power pulsing => low mass tracker, dense calorimeter**

- collisions:
  - luminosity grows with energy
  - minimize beamstrahlung => flat beams 500x5 $nm^2$

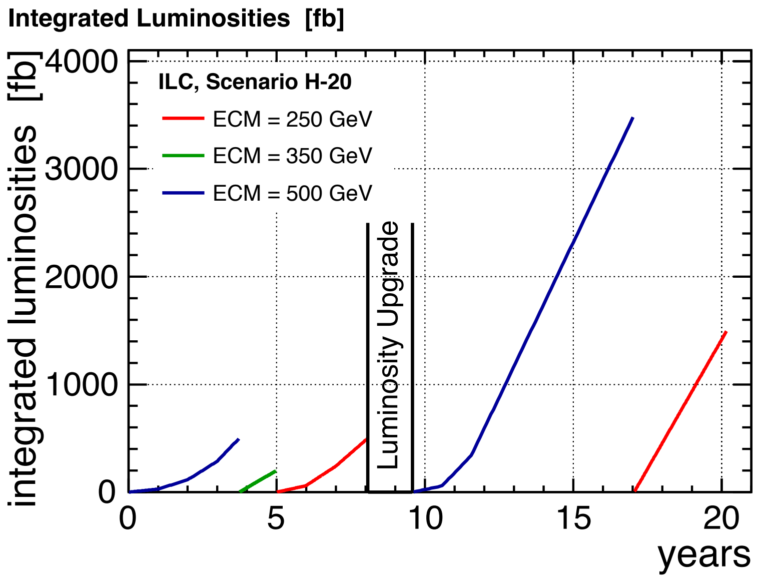



| ECM [GeV] | 250 | 250 | 500 | 250 | 500 | 1000 |
|---|---|---|---|---|---|---|
| rep. rate [Hz] | 5 | 10 | **5** | 10 | 5 | **5** |
| $N_{bunch}$ | 1315 | 1315 | **1315** | 2625 | 2625 | **2625** |
| inst. lumi [$10^{34}$ / $cm^2$ / s] | 0.75 | 1.5 | **1.8** | 3 | 3.6 | **3.6-4.9** |
| **total power [MW]** | **100** | **160** | **160** | **190** | **200** | **300** |

# A possible ILC running scenario

[ILC Parameters Joint WG arXiv:1506.07830]

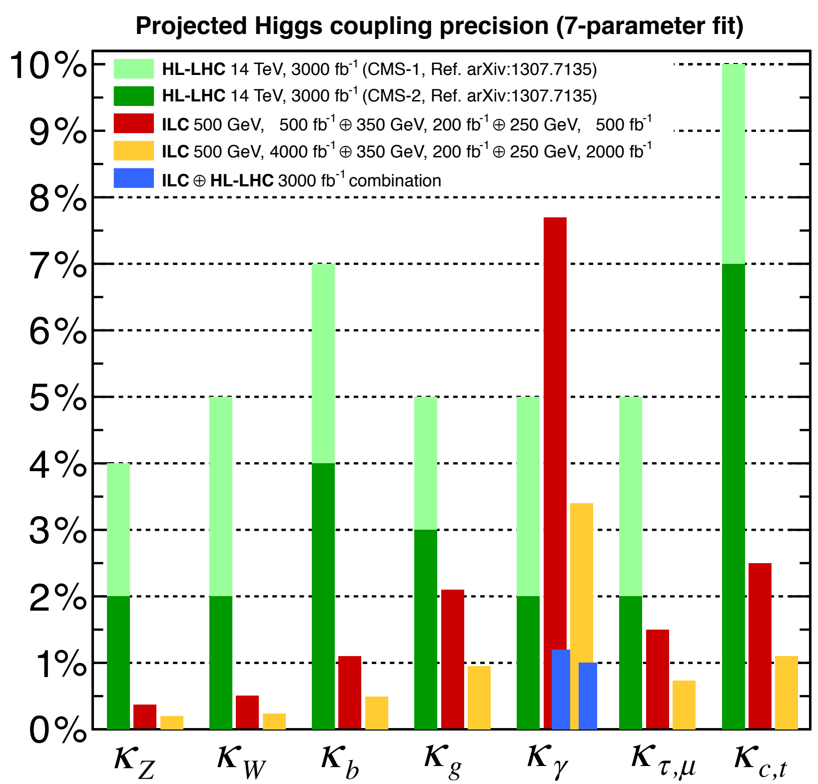
| Stage | ILC500 | | | ILC500 LumiUP | | |
|---|---|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | 500 | 350 | 250 | 500 | 350 | 250 |
| $\mathcal{L}$ [fb$^{-1}$] | 500 | 200 | 500 | 3500 | - | 1500 |
| time [a] | 3.7 | 1.3 | 3.1 | 7.5 | - | 3.1 |



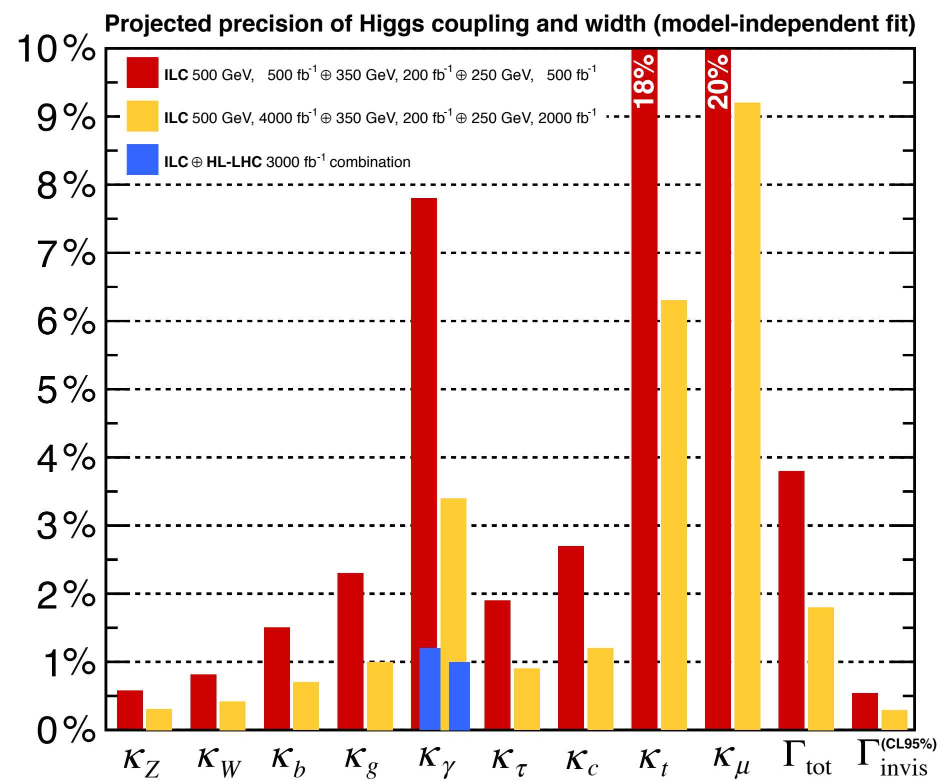

possible 20 year running scenario

# ...and resulting Higgs coupling precisions

**model-dependent (LHC-style)**

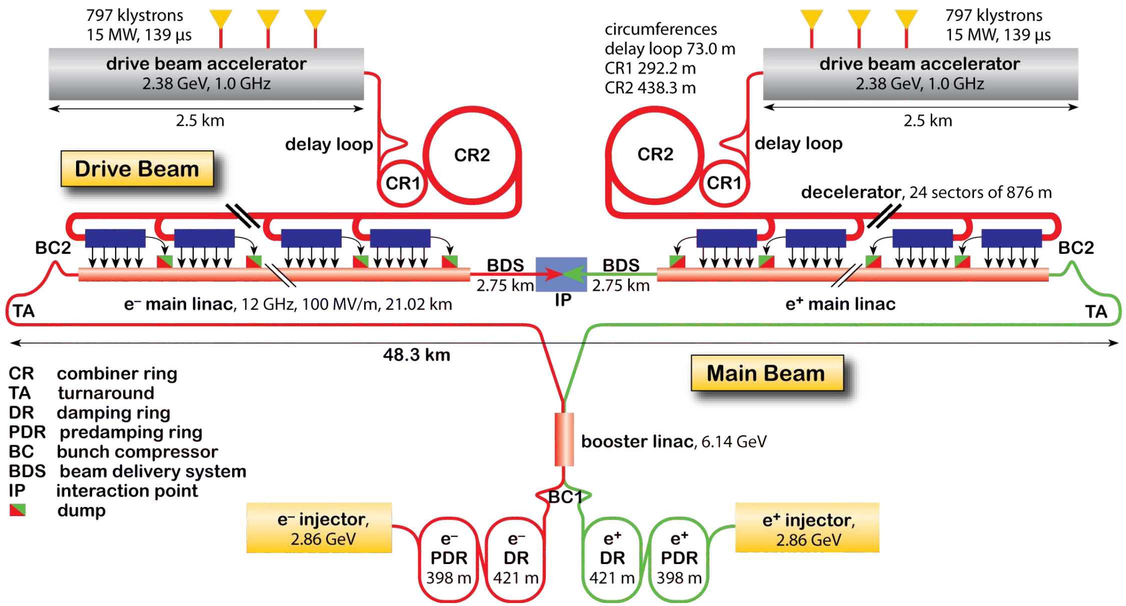



**model-independent**




**For precisions < 1%,**
**systematic uncertainties need to be considered**
**– also in detector design!**

# The Compact Linear Collider




- **350 GeV – 3 TeV**
- trains with 312 bunches
- repetition rate 50 Hz
- total power:
  ~270MW @ 500 GeV
  ~600MW @ 3 TeV

**Detector Challenges:**
- **bunch spacing 0.5 ns**
- **50 Hz: power pulsing? -> cooling needed?**
- **background from beamstrahlung pairs**

**Success of CDR studies:**
**immense background from $e^+e^-$ pairs and γγ-> hadrons can be dealt with**

# Circular $e^+e^-$ Colliders

**CepC (China)**

- 50 km, 2 IPs
- 90 - 240 GeV
- 2 x $10^{34}$ $cm^{-2}s^{-1}$ / IP
- bunch spacing: few μs
- power? ~400-500 MW ?

**FCC-ee (CERN)**

- 80-100 km, 4 IPs
- 90 – 350 GeV
- 28 – 2 x $10^{34}$ $cm^{-2}s^{-1}$ / IP
- bunch spacing: 10 ns - 10 μs
- power aim: 300 MW

**no trains: continuous operation**

**=> good for physics:**
**low per-bunch luminosity, no beamstrahlung**

**⇒ bad for detectors:**
**no power pulsing possible, need cooling!**
**=> low-mass cooling systems**

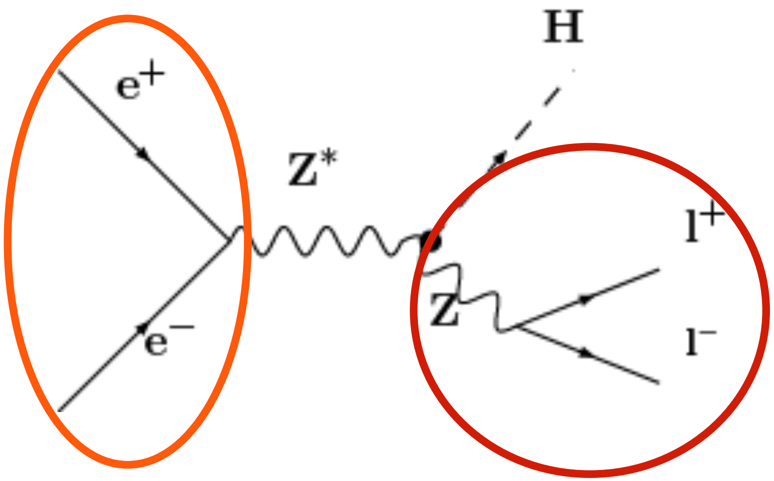
# Detector “R&C”: Requirements and Challenges

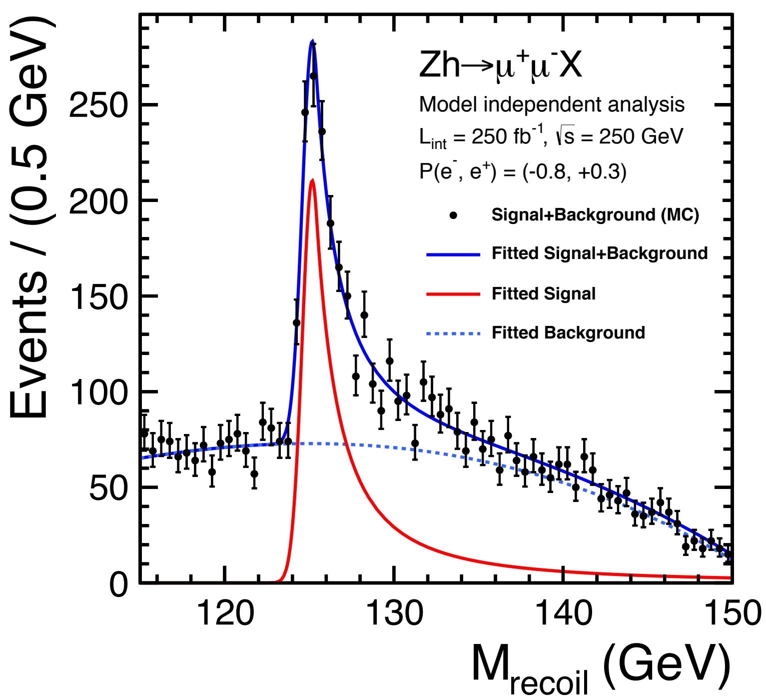
- The key: the total ZH cross section
- Indirect search for new physics: Higgs branching ratios
- Establishing the mexican hat: the Higgs self-coupling
- Identifying Higgs partners: Higgsinos

# The model-independent measurement of $\sigma_{ZH}$

How? → recoil method:

$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$




**initial state:**
**known event-by-event apart from**

- **beam energy spread of accelerator**
- **beam strahlung**
- **ISR**

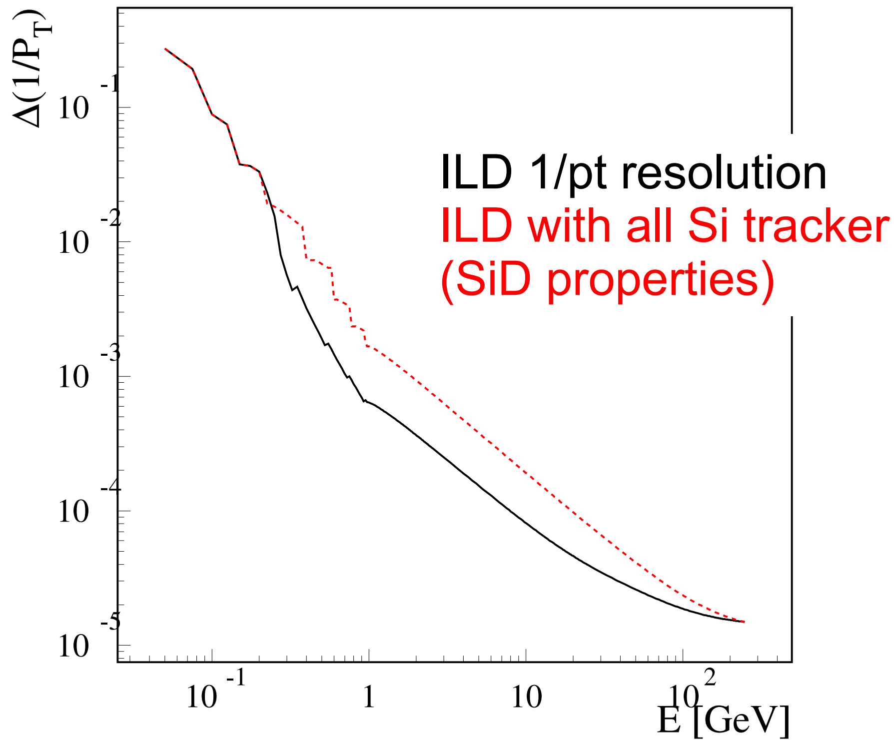
**⇒ shape of peak is detector resolution folded with beam energy spectrum!**

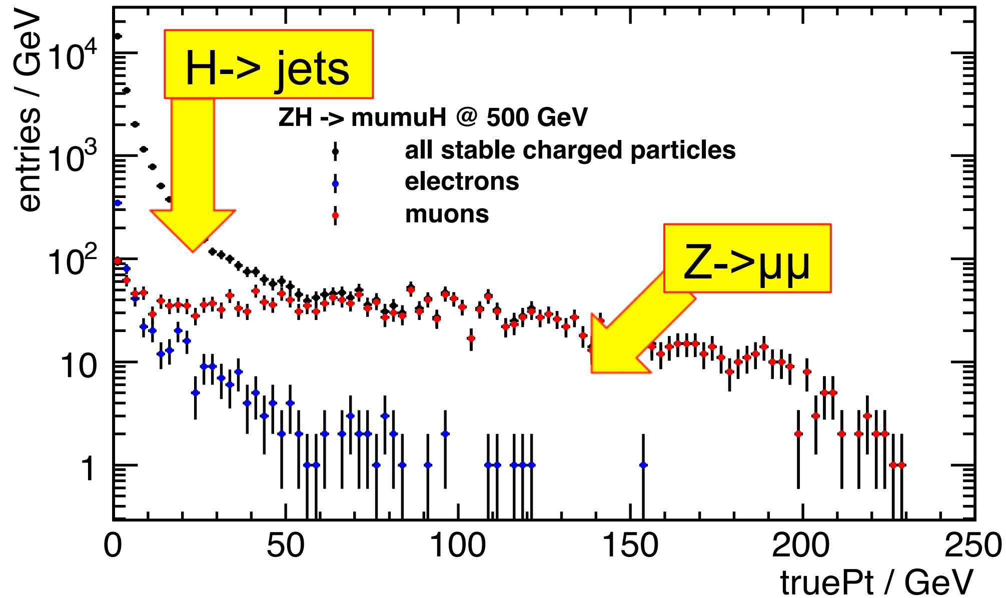
**⇒ nuissance parameter...**

# Higgs Recoil: Momentum resolution

$\sqrt{s}$ = 250 GeV:
  Z ~ at rest, $p_\mu \approx$ 45 GeV

higher $\sqrt{s}$ : Z boosted
  => wide momentum range
  => more challenging!




**Gaseous tracker has less material**
**=> less multiple scattering**

**Challenges (not in simulation so far):**
- **alignment**
- **field distortions in TPC**
- **stability of momentum scale: required to same level as resolution!**

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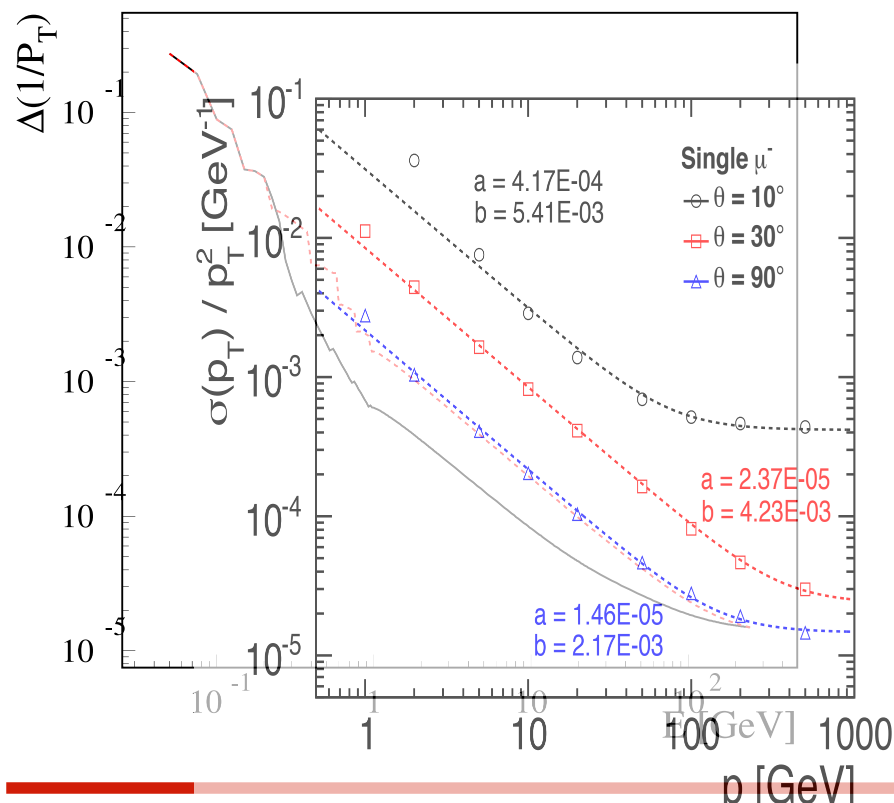


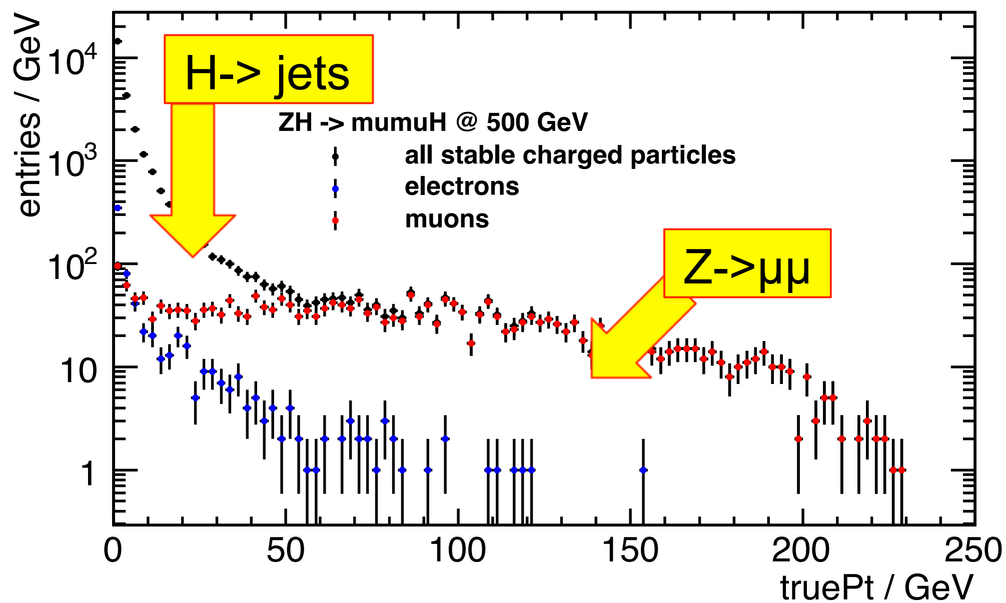


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# Higgs recoil: Systematic Effects

**luminosity**: based on low-angle Bhabha's - current status ~2.6 $10^{-3}$, limited by
**[JINST 8 (2013) P08012]**

- theory (NLO EW ee->4e) ~2 $10^{-3}$
- **energy scale calibration/stability of LumiCal ~1 $10^{-3}$** (if scale known to 2 $10^{-3}$)

**beam polarisation**:

- polarimeter detectors reach 2.5 $10^{-3}$ or better **[JINST 10 (2015) 05, P05014, arXiv:1509.03178]**
- **long-term scale calibration to collision data**, eg WW angular spectra **~ 1 $10^{-3}$**, probably limited by knowledge of collision parameters **[JINST 9 (2014) P07003]**

**shape of peak**:

- beam energy spread, beamstrahlung, ISR: calibrate against Z recoil from ZZ -> μμX
- knowledge of momentum resolution: calibrate against Z lineshape from ZZ -> μμX

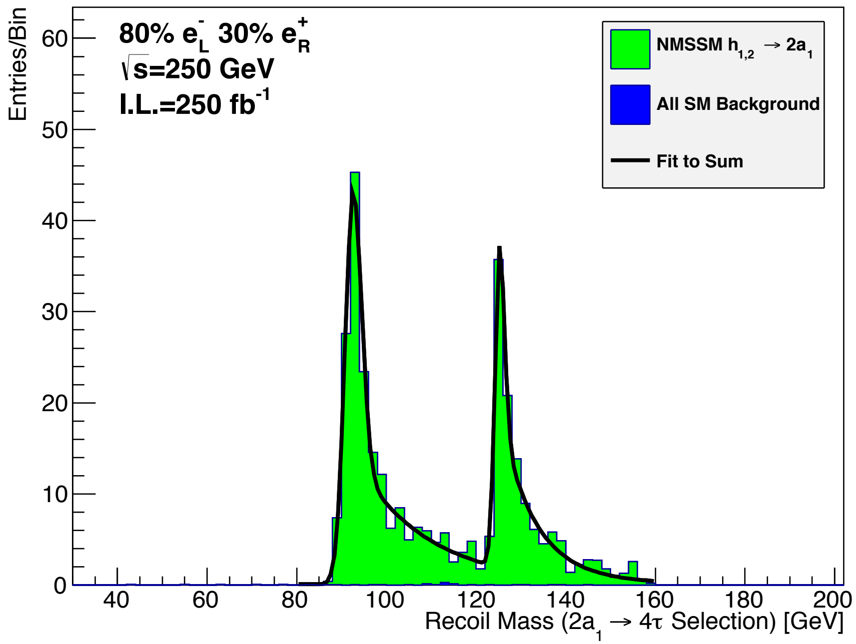
⇒ limited by ZZ statistics to ~ same order as ZH statistical uncertainty

**If no polarisation, no beamstrahlung (eg circular collider):**
**detector challenges:**
- **energy scale of LumiCal**
- **modeling of momentum resolution**

# Another recoil-flavour: Search for light Higgses

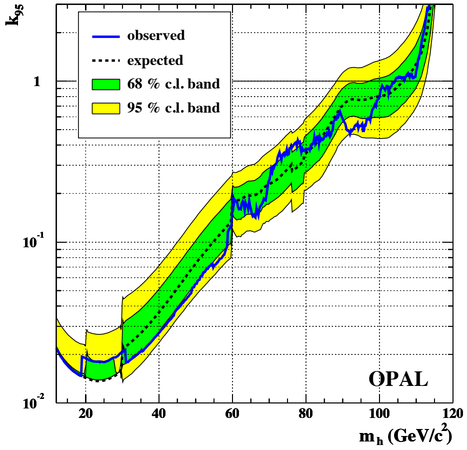
Do the same trick to search for $m_h$ < 125 GeV

- Z boosted even at √s = 250 GeV
- small coupling to Z: tiny signals
- **=> momentum resolution even more crucial!**




C. Potter et al arXiv:1309.0021

- **high interest from theorists / model-builders**
- **currently no detailed ILC simulation study to show accessible range in coupling to Z**

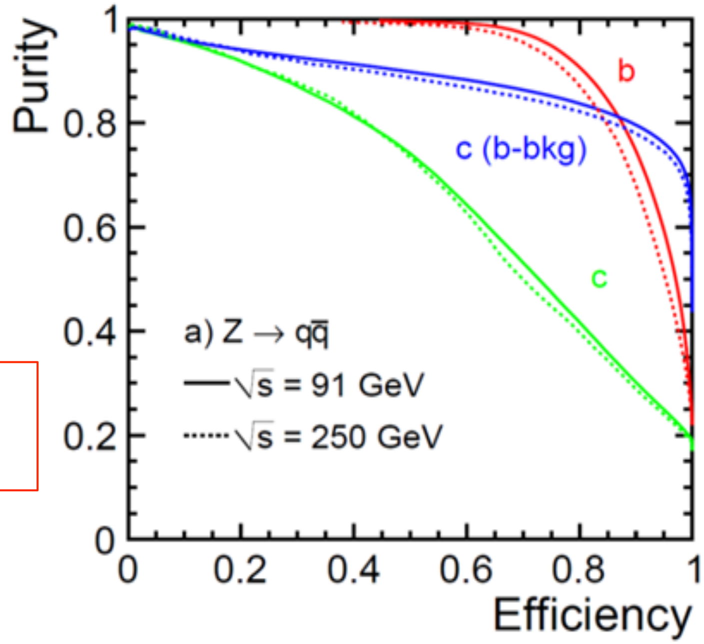


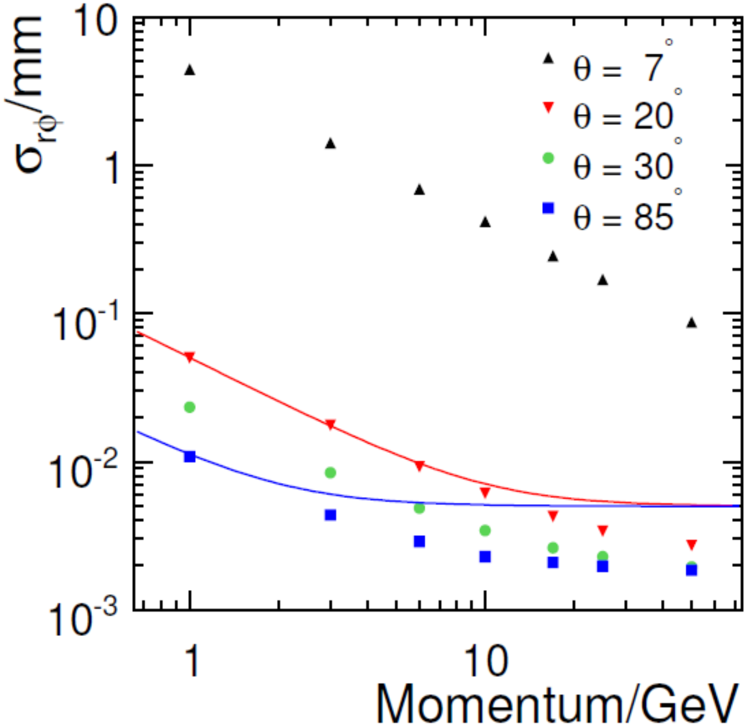

Phys.Lett. B597 (2004) 11-25

# Higgs branching ratios – the usual (ILC) picture

## high performance flavour tag

- secondary / tertiary vertex finding
- needs impact parameter resolution




**full detector simulation**

**2-3 µm**

**“classic” difference between ILD & SiD: choice of time vs point resolution**

# LHC and ILC Vertex detectors

| | LHC | ILC | Comment |
|---|---|---|---|
| Radiation Level | $>10^{16}$ NEQ (neutron equivalent)/cm$^2$ (3ab$^{-1}$) | $10^{10}$NEQ/cm$^2$/yr | **~O($10^5$) difference** FPCCD not a solution at LHC |
| Readout speed requirement (time structure of beam) | 40MHz | 5Hz (ILD FPCCD)<br>100kHz (ILD CMOS)<br>3MHz (SiD) | FPCCD not a solution at LHC |
| Hit density | 2.4hits/cm$^2$/bunch (r=8cm) 12.5ns | ~6hits/cm$^2$/bunch (r=1.6cm) 300ns | Factor of ~3 difference for a given pixel size |

**Key questions for ILC VTX:**

- **do we need single BX readout / time stamping?**
    - SiD: always assumed this will be possible
    - ILD – TDR: conservative => 10-100µs,
      studying impact of pair background on charm-tagging
      => educated choice of time vs point resolution
- **ultra-low mass: aim for 0.15% of a rad. length per double layer**

# Higgs branching ratios: a closer look

## BR(H->bb):

potentially systematically limited for full ILC data set

- b-tagging efficiency?
- b fragmentation function?
- b-jet energy resolution/ scale?
- neutral hadron fraction?

## BR (H->cc / gg / ττ):

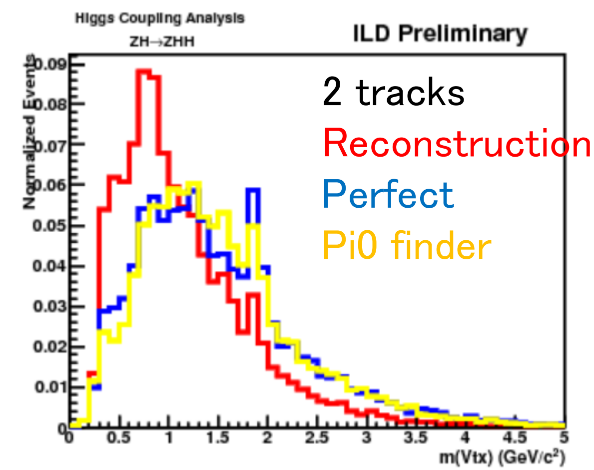
statistically limited even for full ILC data set

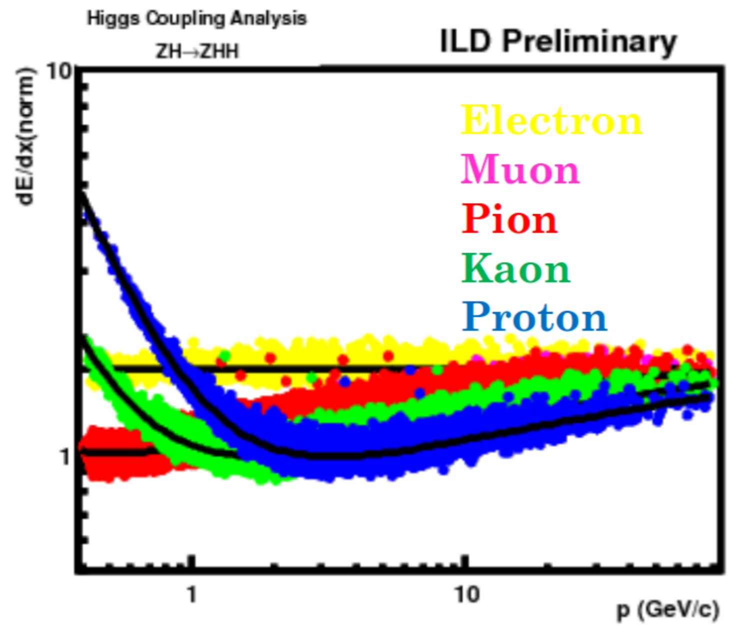
- high performance flavour tag / τ reconstruction
- currently:
  - rely mainly on secondary / tertiary vertex finding
  - impact parameter resolution

**Are there other detector performance aspects which we do not yet consider or cover with the usual benchmarks?**

# Flavour Tag – can be augmented by

- lepton ID in jets: tag semi-leptonic decays => high granular calorimeter & dE/dx
- vertex mass: re-attach $\pi^0 \to \gamma\gamma$ ? (even better: improve $\pi^0$ by kinematic fit)
- particle identification:
  - improved impact parameter resolution with correct mass hypothesis
  - c -> s: which is π, which is K?
  - identify exclusive decay chains
  - and remember systematic uncertainties: verify / re-measure b/c-fragmentation, b/c charged multiplicity, ...




**What is the actual dE/dx resolution of the ILD TPC?**
**What could be done with all-silicon?**

# Higgs Self-Coupling: The Challenge

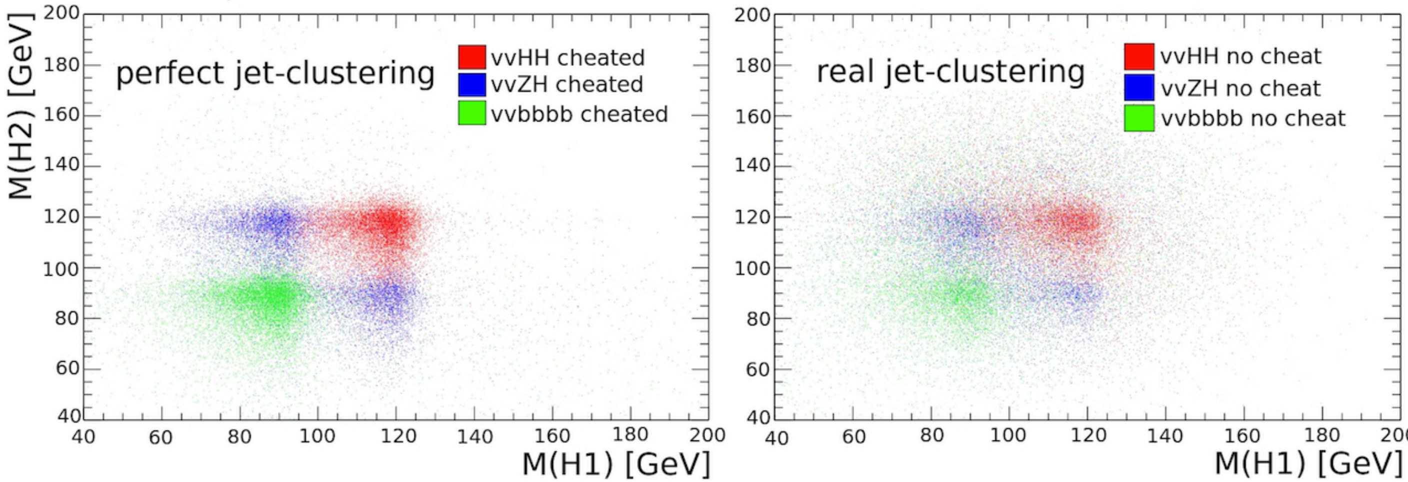
- very low cross section ~0.2 – 0.3 fb @ 500 GeV (depending on polarisation)

many channels, largest BR:

- Zbbbb (36%): 4-6 jets
- ZbbWW* (12%): 6-8 jets

experimental handles:

- flavour tag, lepton ID (s.a.)
- kinematic information => jet energy resolution



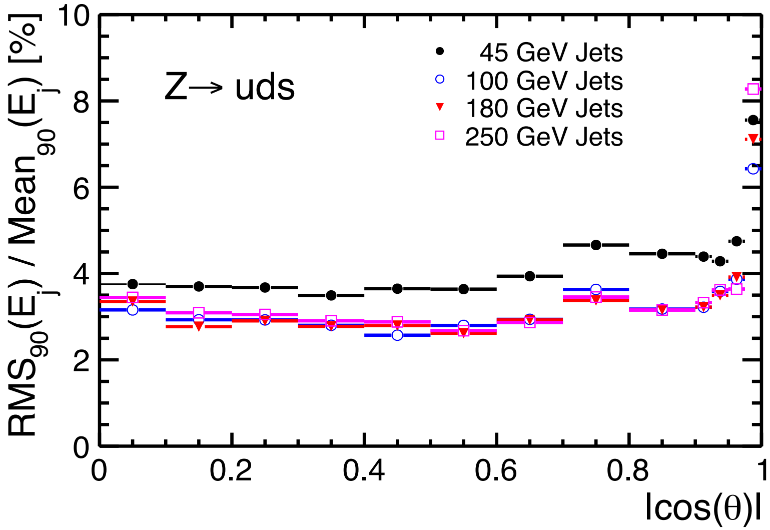

**Excellent particle flow calorimetry: jet energy resolution in multi-jet final states limited by jet clustering**

# Jet Energy Resolution

**Definition (eg in TDR):**

- **ee->uu/dd/ss at fixed energy**
- **no ISR => $E_{jet} = E_{vis} / 2$**
- **$rms_{90} < \sigma$**

**+ isolates detector performance**
**- but beware: not always close to physics**




| particle | Pythia tune | OPAL tune | LEP data |
|---|---|---|---|
| p | 1.2190 | 0.9110 | $0.9750 \pm 0.0870$ |
| n | 1.1661 | 0.8664 | |
| $K^0_S$ | 1.1168 | 1.0150 | $1.0040 \pm 0.0150$ |
| $K^0_L$ | 1.1057 | 1.0164 | |

- PID: $m_p$ (1 GeV) /$E_{jet}$ (50 GeV) = 2% - compare to ~3% resolution!
- combined with flavour-tag: keep decay chains in same yet, incl. vertex-attached $\pi^0$
- neutral hadron fraction:
  - significant impact on JER
  - need to measure at ILC

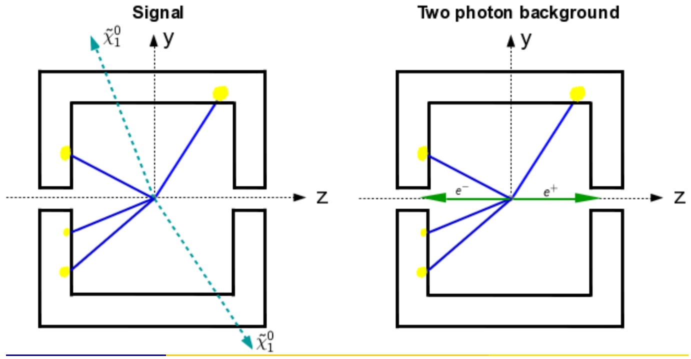
**The key: measure rate of $K^0_S$**

- **$c\tau$ = 2.7 cm**
- **eg 5 GeV $K^0_S$ flies ~30 cm**

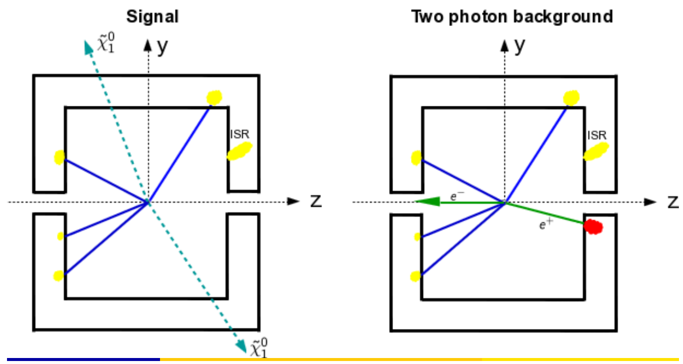
**=> "V0" signature in TPC**

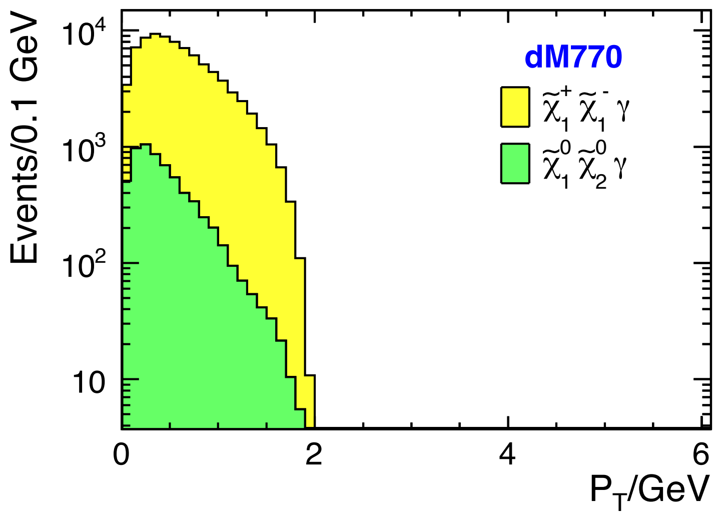
# Higgsinos - the Challenge

- very few, soft visible particles
- in addition: tough background from two-photon processes




**tag with ISR photon in detector**



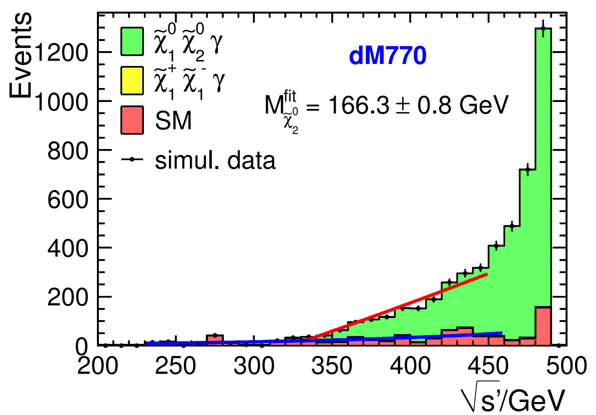



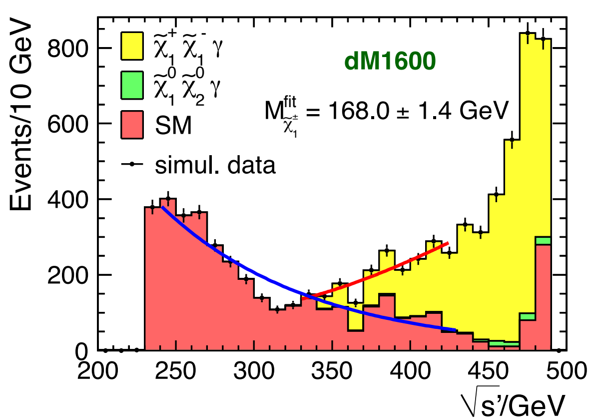

**required to identify Higgsinos:**

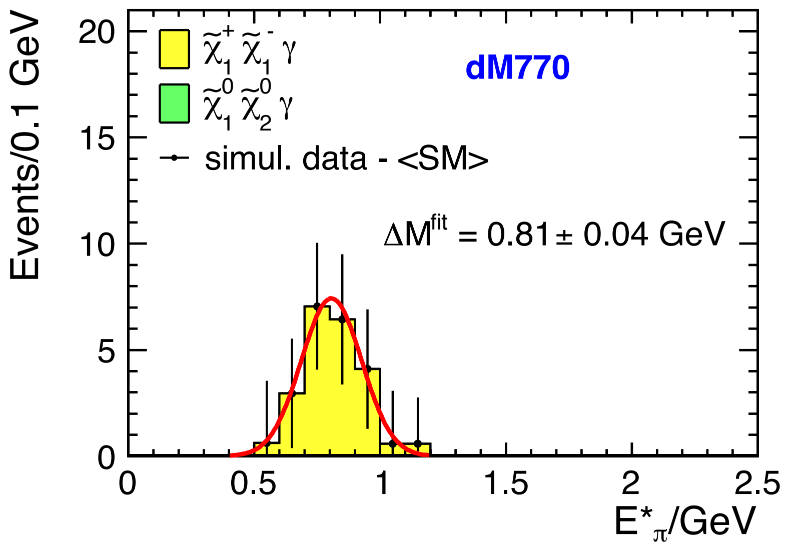
- **semi-leptonic chargino pairs => lepton ID for p<2 GeV**
- **exclusive decays: PID**
- **lifetime: high efficiency for vertex pattern recognition, also at low momenta!**

# Higgsinos – the Analysis

**measure masses from recoil mass against ISR photon √s'**
**=> sensitive to intrinsic ECal resolution**



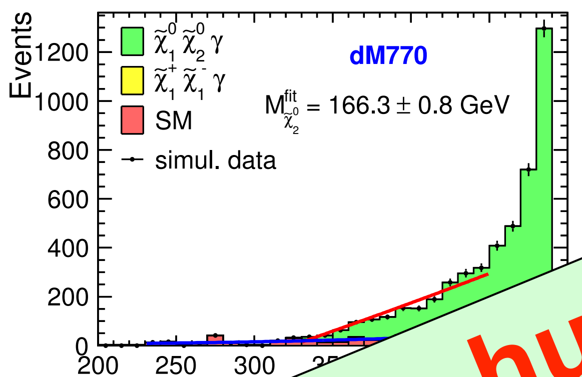



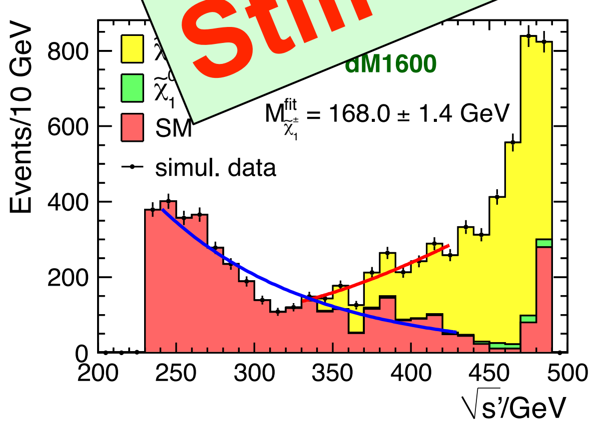

**measure mass difference (~1 GeV!) from decay products boosted into Higgsino rest-frame**

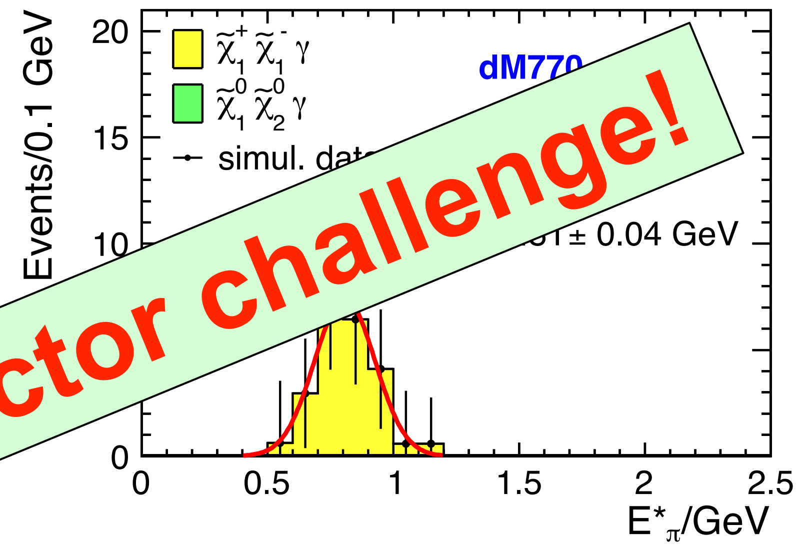
**=> momentum resolution for < 2 GeV tracks crucial**

# Higgsinos – the Analysis

**measure masses from recoil mass against ISR photon $\sqrt{s'}$ => sensitive to intrinsic ECal resolution**




**Still a huge detector challenge!**

**measure mass difference (~1 GeV!) from decay products boosted into Higgsino rest-frame**

**=> momentum resolution for < 2 GeV tracks crucial**

# Conclusions

# Summary

- **A complete picture of the Higgs sector requires unique information from $e^+e^-$ colliders**
  (complementary to hadron colliders, model-independent)
- **Higgs physics relies on all classic detector performance aspects**: JER, flavour tag, momentum res., hermeticity
  - crucial: low mass, low power, high granularity detectors
  - need to consider machine properties => significant differences between ILC/CLIC and circular colliders?
- **underestimated / not sufficiently studied so far:**
  - particle ID: impact on flavour tag, JER
  - helper measurements: eg neutral hadron fraction => $K^0_S$
  - reconstruction and ID of low momentum particles (< 2 GeV)
  - alignment / calibration / stability

# Summary – ILC Detectors

## Status

- well understood detector concepts,  incl. integration, mechanics etc at adequate level for phase of project
- 1st order detector performance in many aspects demonstrated in testbeam, some technical/engineering challenges remain
  => ready to get serious!
- 2nd order performance: more detail, redundancy, control of systematics: might make *the* difference!

## Wish list & challenges

- single bunch crossing read-out / time stamping for vertex detector – while maintaining point resolution !
- alignment, stability; ILD: TPC distortions
- fully demonstrate power-pulsing: 5 Hz .... 10 Hz continuous
- particle ID, low momentum particles

# Thank You

.... for listening

And thanks to all people from whom I stole material while preparing this talk:

- Ties Behnke
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- Klaus Desch
- Masakazu Kurata
- Hale Sert
- Junping Tian

.... and of course SiD & ILD, ILC TDR VOL 4, CLIC CDR, CepC pre-CDR, FCC-ee webpage.....